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Proximity effect in the finite and incommensurate ferromagnet/superconductor systems

Yurii N. Proshin [a,*], Ruslan G. Luchkin [a], Mansur G. Khusainov [a,b]

[a] Kazan State University, Kremlevskaya, 18, Kazan 420008, Russia
[b] Kazan State Tupolev Technical University, Chistopol' 422981, Russia

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ABSTRACT

The original theory of a proximity effect is proposed for the bi- and tri-layered system ferromagnetic metal/superconductor (F/S) in dirty limit. The $F_1/S/F_2$ trilayer is examined more closely. The distinctions in materials, in thicknesses of F layers (d_{f1} and d_{f2}), in parameters interfaces, and in local environments of layers are considered among the causes of incommensurability of trilayer. The peculiar $T_c(d_{f1}, d_{f2})$ interference pattern is predicted for the $F_1/S/F_2$ systems. The reentrant superconductivity and possibility of the better observability of the spin-valve regime are discussed.

1. Introduction

The concept of the proximity effect was introduced by de Gennes [1], studying the properties of the plane contact between the normal metal (N) and the superconductor (S). At the moment, the term "proximity effect" is used for a set of phenomena connecting with the partial transfer of the superconducting properties from superconductor to initially nonsuperconducting matter, which are in intimate contact. As a result, superconductivity appears in the entire heterostructure due to the extent of the transparency of the contact interface.

The proximity effect in the layered F/S structures which consist of the alternating layers of ferromagnetic (F) and superconducting (S) metals has additional peculiarities in comparison with the N/S systems, because superconductivity and ferromagnetism are two antagonistic ordering phenomena. After pioneer works [2], the considerable success in the experimental and theoretical examination of proximity effect in the layered F/S systems is reached (see reviews [3–6] and references therein). The superconductivity in these systems is due to two competing mechanisms of pairing: the BCS one in the S layers and the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) one in the F layers. As a rule, the multilayered systems with a high degree of symmetry (the materials, their interfaces, and boundary conditions and so on are considered with identical parameters) were explored.

The finiteness of the F/S systems can lead to incommensurate F/S structures. It is linked with nonequivalence of layers which are made of identical material, but they have different local surrounding and, as a consequence, different boundary conditions. In turn the hierarchy of critical temperatures T_c may arise, as shown for the four-layered $F/S/F'/S'$ structures [7]. In the works [8], the partially nonsymmetry of the $Nb/Pd_{0.81}Ni_{0.19}$ hybrids (with nine internal layers of superconducting Nb) have been experimentally and theoretically investigated regarding their finiteness.

In common case, the transparencies of different F/S interface may be dissimilar. The different F metals or/and different S metals may be used for fabrication of the layered F/S system. The layers may have different parameters: coherence lengths, thicknesses, free path length, Fermi velocities, zone parameters, exchange fields, and so on. Fauré et al. [9] have shown in *simple Cooper limit* for the $F_1/S/F_2$ trilayer that the differences in the ferromagnetic layer thicknesses (d_f), exchange fields (I), interface transparencies, and spin–flip scattering times lead to significant modifications of phase diagrams and change (amplify or attenuate) the spin-valve effect.

The spin-valve regime is possible for an $F/S/F$ trilayer, because the critical temperature T_c for the antiferromagnetic

* Corresponding author. Tel.: +7 843 231 5342; fax: +7 843 238 0994.
E-mail address: Yurii.Proshin@ksu.ru (Y.N. Proshin).

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